

The metal-insulator transition in Si:X: Anomalous response to a magnetic field.

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The zero-temperature magnetoconductivity of just-metallic Si:P scales with magnetic field, H , and dopant concentration, n , lying on a single universal curve: $\sigma(n, H)/\sigma(n, 0) = G[H^{-\delta}\Delta n]$ with $\delta \approx 2$. We note that Si:P, Si:B, and Si:As all have unusually large magnetic field crossover exponents near 2, and suggest that this anomalously weak response to a magnetic field is a common feature of uncompensated doped semiconductors.

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The metal-insulator transition (MIT) that occurs in doped semiconductors and in amorphous metal-semiconductor mixtures is a continuous phase transition [1,2,3]. Some difficulty has been encountered in demonstrating the scaling that is expected to hold near such a transition. Scaling with temperature and dopant concentration has been shown to hold for Si:P in the presence of a magnetic field of 75 kOe [2]. However, the conductivity does not appear to scale with temperature in the absence of a magnetic field: scaling [4] is obtained only if one chooses a critical conductivity exponent, $\mu \approx 0.29$, considerably smaller than the value found experimentally [5,6,7]. On the other hand, scaling of the zero-temperature conductivity has been demonstrated with magnetic field for p-type Si:B [8], albeit with an anomalously large magnetic field crossover exponent near 2. This raises the issue whether the anomalously weak response to a magnetic field is due to the spin-orbit scattering present in boron-doped silicon, or whether it is a general feature of uncompensated doped semiconductors near the metal-insulator transition. Si:P is considered the archetypical strongly correlated disordered system, and is used as a standard against which newer materials are compared [9]. It is therefore of great fundamental interest to determine the functional form of the magnetoresistance close to its MIT.

To address these issues, we report measurements of the magnetoconductivity of Si:P. Detailed analysis of data taken at low temperatures in magnetic fields to 90 kOe allows us to identify separate, temperature-dependent components, yielding reliable determinations of the zero-temperature conductivity. Our results demonstrate that the zero-temperature conductivity scales with magnetic field and dopant concentrations, $\sigma(n, H)/\sigma(n, 0) = G(H^{-\delta}\Delta n) = F(H/H^*)$, with a crossover exponent, $\delta \approx 2$, comparable to the anomalously large crossover

exponent of Si:B [8]. Moreover, earlier data of Shafarman et al. [10] indicate that the magnetoconductance of Si:As strongly resembles that of Si:P, scaling with a similar crossover function and exponent. We note that all the silicon-based doped semiconductors exhibit an anomalously weak response to a magnetic field, and suggest that this is a feature of the universality class of silicon-based doped semiconductors that is currently not understood.

Four Czochralski-grown Si:P samples were used in our studies with dopant concentrations 3.60, 3.66, 3.95 and $4.21 \times 10^{18} \text{ cm}^{-3}$. Based on a critical concentration $n_c = 3.46 \times 10^{18} \text{ cm}^{-3}$ [7], this corresponds to $1.04n_c$, $1.06n_c$, $1.14n_c$, and $1.22n_c$. Measurements were taken at temperatures between 0.037 K and 0.5 K in magnetic fields up to 90 kOe. Sample characterization and measurement techniques are described elsewhere [7,11].

At temperatures sufficiently low that corrections due to localization are small, finite temperature corrections due to interactions are expected to yield a conductivity [12,13,14,15]:

$$\sigma(n, T) = \sigma(n, 0) + A(n)T^{\frac{1}{2}}. \quad (1)$$

in the absence of a magnetic field. The slope $A(n) = (\sigma_{ex} - \sigma_{Har})/T^{1/2}$, where the exchange term, σ_{ex} , and the Hartree term, σ_{Har} , contribute with opposite sign. The Hartree term consists of a $S_z = 0$ channel, σ_{s0} , which is independent of magnetic field, and field-dependent $S_z = \pm 1$ contributions, $\sigma_{s\pm}$, which are suppressed in very large fields. Thus:

$$A(n)T^{\frac{1}{2}} = (\sigma_{ex} - \sigma_{s0}) - \sigma_{s\pm}. \quad (2)$$

For doped semiconductors in the absence of a magnetic field, the slope $A(n)$ is net positive near the transition and changes sign as one moves away toward higher dopant concentration n . For the four specimens used in our study, the slope is positive for the sample closest

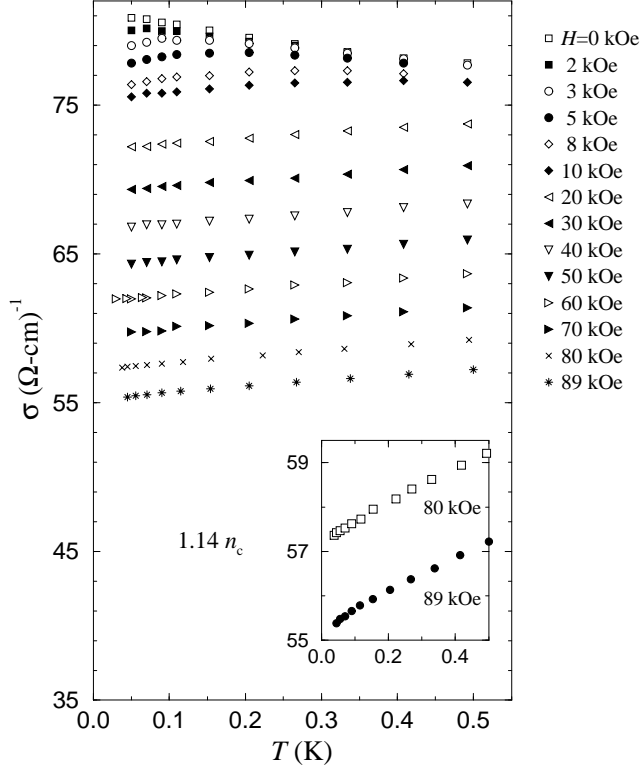


FIG. 1. Conductivity σ versus temperature in various magnetic fields for dopant concentration $n = 1.14n_c$. The inset shows data in high magnetic fields on an expanded scale.

to the transition ($n = 1.04n_c$), $A \approx 0$ for the sample with $n = 1.06n_c$, and the two samples furthest from the transition have net negative slopes A . The samples used in our experiments thus span concentrations that include temperature coefficients for the conductivity that are positive, zero and negative in the absence of a field.

The conductivity of one sample (for which A is net negative) is plotted in Fig. 1 as a function of temperature at various fixed magnetic fields. The inset shows the conductivity in large magnetic field on an expanded scale. The curves are parallel to each other in fields above 10 or 20 kOe, indicating that the temperature dependence in high magnetic fields is independent of the field. Similar behavior is found for the other three samples. This is also demonstrated in Fig. 2 (a), where the conductivity is shown as a function of magnetic field for one sample at four different temperatures. Again, it is clear that the curves at different temperatures are parallel to each other in fields above 10 or 20 kOe. Thus, in sufficiently high fields the dependence on temperature is independent of field, corresponding to the term $(\sigma_{ex} - \sigma_{s0})T^{1/2}$ in Eq. (2) above. As shown in Fig. 2 (b), all the curves can be brought into coincidence in high magnetic fields by subtracting this temperature-dependent term from the total conductivity. Deviations occur in small fields, becoming

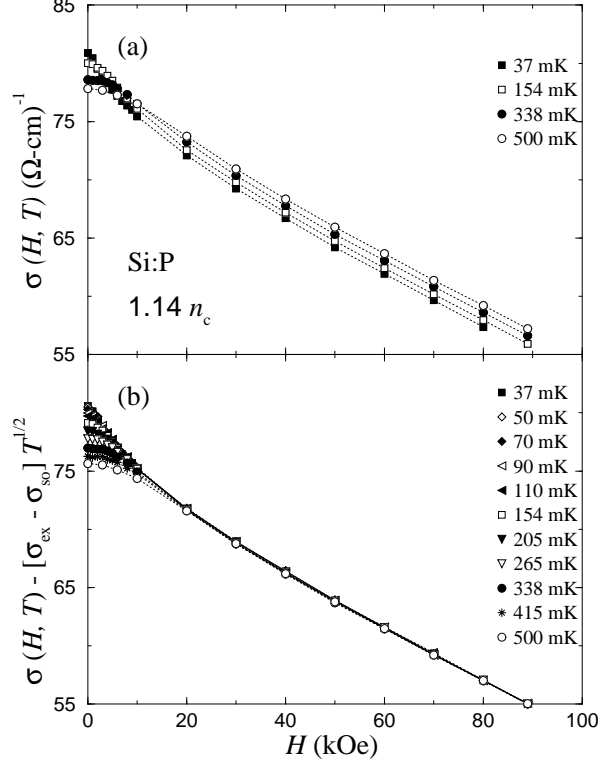


FIG. 2. (a) For dopant concentration $n = 1.14n_c$, the conductivity σ versus magnetic field H at four different temperatures, as labeled. (b) The conductivity minus $(\sigma_{ex} - \sigma_{s0})T^{1/2}$ plotted as a function of magnetic field (see text); the prefactor $(\sigma_{ex} - \sigma_{s0})$ varies from sample to sample. Note that all curves coincide above 10 or 20 kOe.

increasingly pronounced as the temperature increases: the conductivity flattens below a magnetic field H given approximately by $g\mu_B H \approx k_B T$. This corresponds to the triplet channel contribution, $\sigma_{s\pm}T^{1/2}$, of Eq. (2).

The curves shown in Fig. 2 (b) for 37, 50 and 70 mK differ from each other by small amounts compared to the overall change of the conductivity with magnetic field; the lowest temperature data are thus close to the $T = 0$ curve on this scale. Setting $\sigma(H, 0) \approx \sigma(H, 37 \text{ mK})$, we show $\sigma(H, 0)/\sigma(0, 0)$ plotted as a function of H for all four samples in Fig. 3 (a). These four very similar curves can be collapsed onto a single curve by appropriate choices of a scaling parameter H^* , as shown in Fig. 3 (b). We have thereby demonstrated that the zero-temperature conductivity scales with magnetic field, taking on the form [16,17]:

$$\frac{\sigma(n, H)}{\sigma(n, 0)} = G(H^{-\delta} \Delta n) = F\left(\frac{H}{H^*}\right) \quad (3)$$

with a crossover function $G(H^{-\delta} \Delta n)$, a magnetic-field crossover exponent δ , and a scaling parameter H^* that should obey a power law in the critical region, $H^* \propto \Delta n^{1/\delta}$.

We note that scaling appears to hold quite well for the samples that have negative as well as positive zero-field slopes A . The crossover function of Fig. 3 (b) exhibits complex behavior at low fields, and becomes linear with magnetic field at high fields. The inset to Fig. 3 (b) shows H^* versus $\Delta n \equiv (n - n_c)$ on a log-log scale, using $n_c = 3.46 \times 10^{18} \text{ cm}^{-3}$ [7]. (Data are included in the inset for samples measured earlier and not otherwise presented in this paper.) There appear to be deviations from a straight line (power law behavior) at the highest dopant concentration, perhaps indicating that the last sample is not in the critical region. Additional careful studies are needed to determine the breadth of the critical regime. The (inverse) slope yields a magnetic-field crossover exponent $\delta \approx 2$, which is unusually large.

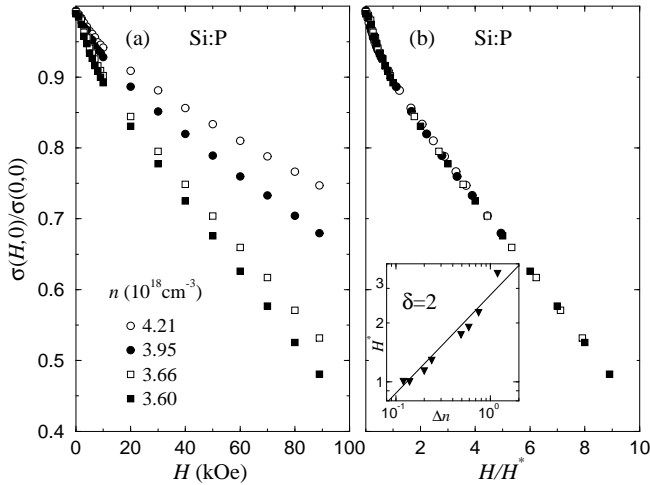


FIG. 3. (a) The ratio $\sigma(H,0)/\sigma(0,0)$ versus magnetic field H for four just-metallic Si:P samples with dopant concentrations as labeled; $n_c = 3.46 \times 10^{18} \text{ cm}^{-3}$. (b) Scaled curves of $\sigma(H,0)/\sigma(0,0)$ versus H/H^* (using $n = 3.60 \times 10^{18} \text{ cm}^{-3} = 1.04n_c$ as the reference sample for which $H^* = 1$). The inset shows H^* versus $\Delta n = (n - n_c)$ on a log-log scale, and includes additional samples measured earlier.

A similar analysis yields the curves shown for Si:B [8] in Figs. 4 (a), and scaling is obtained for appropriate choices of the scaling parameter H^* , as shown in Fig. 4 (b). The inset is a plot of H^* versus Δn on a log-log scale. Again, deviations from power-law behavior are apparent at the higher dopant concentrations, implying that these are outside the critical range; the crossover exponent $\delta \approx 1.9$.

Si:P and Si:B both have large δ 's near 2. However, their crossover functions are quite different, as illustrated in Fig. 4 (b) where both are shown for comparison. The effect of a magnetic field is considerably stronger in the case of Si:B: a 90 kOe field easily drives a just-metallic sample into the insulating phase. The magnetoconductance of Si:B exhibits the theoretically expected $H^{\frac{1}{2}}$ behavior [14,18] over a broad range of fields. On the other

hand, the magnetoconductance of Si:P displays $H^{\frac{1}{2}}$ dependence only in moderate magnetic fields and becomes strictly linear in H at higher fields; the conductivity of Si:As exhibits very similar behavior [10] to Si:P. We note that the theory of refs. [14] and [18] is valid only outside the critical region, and the behavior near the transition is not known. The observed deviation from $H^{\frac{1}{2}}$ may simply reflect the fact that sufficiently high magnetic fields drive our samples toward the transition and into the critical range. The scaling found in this paper suggests that a magnetic field drives samples into the critical regime for $H > H^* \propto \Delta n^{1/\delta}$.

In both Si:B and Si:P, there are also clear deviations from $H^{\frac{1}{2}}$ behavior in small magnetic fields: attempts to fit to this form yield a zero-field conductivity that is decidedly inconsistent with the measured value. This unexpected behavior in small magnetic fields is also reflected in anomalous temperature-dependence at low temperatures, and will be discussed elsewhere.

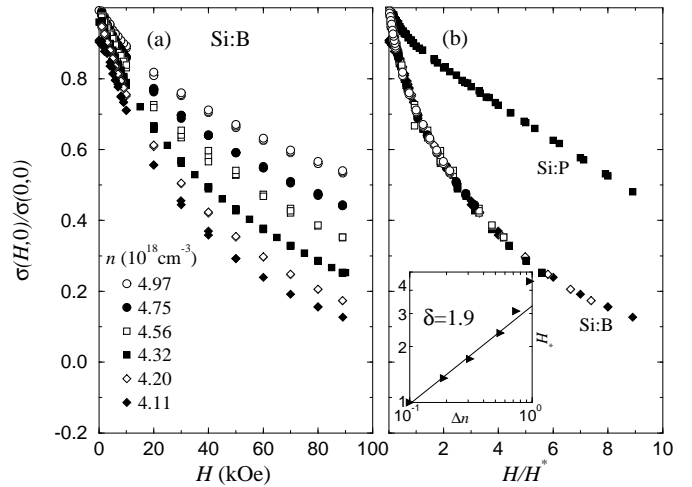


FIG. 4. (a) The ratio $\sigma(H,0)/\sigma(0,0)$ versus magnetic field H for just-metallic samples of Si:B with dopant concentrations as labeled; $n_c \approx 4.01 \times 10^{18} \text{ cm}^{-3}$. (b) Scaled curves for Si:B of $\sigma(H,0)/\sigma(0,0)$ versus H/H^* . For comparison, the upper curve shows data for Si:P. The inset shows H^* versus $\Delta n = (n - n_c)$ on a log-log scale (using $n = 4.11 \times 10^{18} \text{ cm}^{-3} = 1.025n_c$ as the reference sample for which $H^* = 1$).

To summarize, the zero-temperature conductivities of Si:P and Si:B both scale as a function of magnetic field and dopant concentration, $\sigma(n, H)/\sigma(n, 0) = F(H/H^*) = G(H^{-\delta} \Delta n)$, with an anomalously large crossover exponent near 2. Analysis of published data for Si:As [10] indicates that scaling is also obeyed in this system, again with a crossover exponent substantially larger than 1. In contrast, theory predicts crossover exponents considerably smaller than 1: orbital effects are expected to give a magnetic field crossover exponent $\delta = 1/2$ [16], and calculations done to date indicate that coupling of the magnetic field to the electrons' spin yields an even

smaller value [19,20]. Since $(\Delta n) \propto H^\delta$, this implies that very near the transition, a small magnetic field should induce a very large change in critical concentration. The large crossover exponent found in our experiments signals instead that for both n-type and p-type uncompensated doped silicon, a small magnetic field induces a small change in the critical concentration. This anomalously weak response to a magnetic field is a feature of the universality class of silicon-based doped semiconductors that warrants further study.

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